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STUDY OF THE EFFECT OF WEATHER ON ROAD CONSTRUCTION: A SIMULATION MODEL [1]

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ABSTRACT

Daily engineering records from two road construction projects near Jefferson City, Mo., for the years 1965–68 were combined with soil moisture and precipitation measurements from nearby meteorological stations to develop a model capable of producing an experimental series describing conditions suitable for road building activities. This model was then applied to a long-term series of daily precipitation records for Jefferson City (1918–65) to calculate road construction conditions over this period. Monthly and seasonal statistics describing the feasibility of various levels of road building activity are presented for the 48-yr period. These statistics include second-order Markov chain probability estimates of working and nonworking days. Aside from the inferences which can be directly drawn from the seasonal and monthly descriptive data, the statistics may have value in developing further simulation models for estimating the effects of various management strategies.

1. INTRODUCTION

Effects of weather conditions on particular components of the economy have been considered by a number of investigators. Studies assessing the association between weather and agricultural production (Maunder 1968), housing starts (Musgrave 1968), retail trade (Linden 1961), electrical power production (Johnson et al. 1969), natural gas consumption (McQuigg and Thompson 1966), and agricultural land prices (Johnson and Haigh 1970) are among those of more recent vintage. The weather sensitivity of the construction industry in the United States has also been considered (Russo 1966, Theil 1966, U.S. Department of Commerce 1966), but little attention has been devoted to the road building sector. Expenditures for road construction are, however, an important part of the total expenditure on construction and of the budgets of Federal, State, and local governments from which they are financed.

In this study, effects of climatic variables on the highway construction industry are estimated through their influence on working conditions during the main construction months. Data from two construction projects are combined with a soil moisture index to obtain conditions under which construction activities can proceed. This relationship is used to generate an experimental series of working conditions based on available weather data. The resulting series of simulated working conditions are then assessed regarding their potential as aids to planning and scheduling highway construction projects.

2. DATA COLLECTION

CONSTRUCTION DATA

Road construction operations data were obtained from two sources: the Missouri State Highway Commission and two private contracting companies.[5] Although the operational data were kept mainly for accounting purposes, they did contain reasonably good information on the quantity of material moved per machine per man per week for a 4½-yr period during which road construction was performed in the vicinity of Jefferson City, Mo. In addition, the operational records indicated the type of work, if any, performed each day. From these data, each day during the sample 4½-yr period was classified into one of three categories by the resident engineer on the construction project: (1) full workday, (2) no-work day, or (3) a partial workday.[6] Saturdays, Sundays, and holidays were excluded unless work happened to be done on those days.

METEOROLOGICAL DATA

Both of the road construction projects studied were located a few miles southwest of Jefferson City, Mo. The nearest climatological station is located about 2 mi from the construction site, at Lincoln University. Initially, daily precipitaton data for the period Jan. 1, 1966, through June 30, 1969, were used because this covered the period for which the road construction data were available. Later, daily precipitation data from Jefferson City for the 50-yr period beginning with Jan. 1, 1918, were used in obtaining the experimental series based on the observed road construction data. Daily soil moisture measurements and climatological observations from the University of Missouri Atmospheric Science Department station near Columbia were also used in developing the soil moisture index used in the analysis.

3. SOIL MOISTURE INDEX MODEL

Development of the soil moisture index model to be applied to the road construction industry required con-

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[5] The fine cooperation of the J. A. Tobin Construction Co., Kansas City, Kans., and the Clarkson Construction Co., Kansas City, Mo., is acknowledged. It would be misleading to suggest that the operational data available were entirely adequate for use in research. However, in all fairness, it should be noted that these data were not originally collected for that purpose.

[6] Classifications were consistent between company records and State Highway Department records and, in as much as they could be compared with other company records, they appeared to be consistent over the 4½-yr period.

TABLE 1.—*Index of daily soil moisture losses (in.)*[a]

Day of decline (*n*)	Seasons: Summer (June 11 through September 30)			Transition (October 1–December 9, April 16–June 10)			Winter (December 10 through April 15)		
	A	B	C	A	B	C	A	B	C
1	0.20	0.11	0.06	0.16	0.11	0.06	0.12	0.06	0.03
2	.16	.09	.05	.13	.09	.05	.10	.05	.02
3	.13	.08	.04	.11	.07	.04	.08	.04	.01
4	.11	.07	.03	.09	.06	.03	.06	.03	.01
5	.09	.06	.02	.07	.05	.02	.05	.02	.01
6	.07	.05	.01	.06	.04	.01	.04	.01	.01
7	.06	.04	.01	.05	.03	.01	.03	.01	.01
8	.05	.03	.01	.04	.02	.01	.02	.01	.01
9	.04	.02	.01	.03	.01	.01	.01	.01	.01
10	.03	.01	.01	.02	.01	.01	.01	.01	.01
11	.02	.01	.01	.01	.01	.01	.01	.01	.01
≥12	.01	.01	.01	.01	.01	.01	.01	.01	.01

[a] The values in this table are believed to be representative of soil moisture losses from a bare silt loam soil. Applications of this model to areas with different soil types would require revision of this table.
A If soil moisture index of previous day is >1.20
B If soil moisture index of previous day is 0.60 through 1.20
C If soil moisture index of previous day is <0.60

TABLE 2.—*Examples of soil moisture index computations*

1966 date	Soil moisture index previous day (in.)	Maximum possible oss (in.)	Precipitation on day *n* (in.)	Is precipitation≥ maximum loss?	Actual soil moisture loss (in.)	Soil moisture index on day *n* (in.)
May 24	1.56	0.16	1.61	yes	0.16	1.80
May 25	1.80	.16	0.00	no	.13	1.67
May 26	1.67	.16	.00	no	.11	1.56
May 27	1.56	.16	.00	no	.09	1.47
May 28	1.47	.16	.00	no	.07	1.40
May 29	1.40	.16	.00	no	.06	1.34
May 30	1.34	.16	.00	no	.05	1.29
May 31	1.29	.16	.00	no	.04	1.25
June 1	1.25	.16	.00	no	.03	1.22
June 2	1.22	.16	.00	no	.02	1.20
June 3	1.20	.11	.17	yes	.11	1.26
June 4	1.26	.16	.00	no	.13	1.13
June 5	1.13	.11	.00	no	.07	1.06
June 6	1.06	.11	.00	no	.06	1.00
June 7	1.00	.11	.18	yes	.11	1.07

sideration of two types of information. First, it was necessary to obtain information on daily soil moisture for a period comparable to the period over which the construction data were available. This information was obtained from measurements made with a neutron meter and a weighing lysimeter on the University of Missouri South Farm near Columbia and approximately 30 mi from the construction sites. Secondly, the moisture data had to be combined with information related to trafficability for heavy equipment. Ideally, this second type of information would have come from the company and the highway department records on the construction projects. Unfortunately, the precision of the records did not permit such refined estimates as those necessary for relating trafficability. As an alternative, experimental information developed by the U.S. Department of Agriculture and U.S. Army Corps of Engineers (1959) for relating soil moisture and trafficability was employed. These data, modified according to the available information from the construction projects, are presented in table 1. Results of initial use of this table with observed soil moisture values led to some additions to, and alterations of, the reported tabular values. In this connection, it should be noted that the values shown in table 1 for the column labeled A were in part taken from the U.S. Department of Agriculture and U.S. Army Corps of Engineers (1959) trafficability study. The values for columns labeled B and C were the result of adjustments made following comparison of computed against observed soil moisture values for the University of Missouri South Farm meteorological station. The modified data are shown in table 1 as estimated daily average soil moisture losses.

Daily soil moisture index values were computed using the following relationship:

$$\mathrm{SM}(n)=\mathrm{SM}(n-1)+\mathrm{PRECIP}(n)-\mathrm{LOSS}(n) \qquad (1)$$

with the constraint that $\mathrm{SM}(n)\leq\mathrm{SM(max)}$. $\mathrm{SM}(n-1)$ is the soil moisture index for day $n-1$, $\mathrm{SM}(n)$ is the soil moisture index for day n, $\mathrm{PRECIP}(n)$ is the observed precipitation for day n, $\mathrm{LOSS}(n)$ is the index of soil moisture loss for the proper season and column (from table 1) and SM(max) is the upper limit for the soil moisture index. In the case of the road construction project near Jefferson City, Mo., this upper limit was set at 1.80 in., a value which approximates the maximum available soil moisture in the top 12 in. of soil.

The selection of a soil moisture loss value which is to be taken from table 1 proceeds as follows:

1. On days when precipitation was greater than or equal to the maximum soil moisture loss for the particular column in table 1, the actual soil moisture loss for that day was considered to be the maximum for the appropriate column.
2. On subsequent days, if the precipitation was less than this maximum amount, the soil moisture loss from the table was entered for $n=1, 2, \ldots, 12$, depending on the number of days since the daily precipitation equaled or exceeded the maximum soil moisture loss.

Results of some typical calculations are shown in table 2. For example, on June 2, 1966, the soil moisture index at the end of the day was 1.20 in., implying that the maximum soil moisture index loss on the following day was 0.11 in. (see column B of the transition season). On June 3, 1966, the precipitation was 0.17 in., which was more than the maximum soil moisture index loss of 0.11 in. The net change in soil moisture for the day was therefore set at +0.06 in. The soil moisture at the end of June 3, 1966, was therefore 1.26 in. The precipitation on the following day was zero, and the net change of soil moisture index was therefore 0.13 (on the second day of decline in moisture zone A, transition season; note that it is not moisture zone B since the soil moisture was greater than 1.20 in.), giving a soil moisture at the end of June 4, 1966, of 1.13 in. Similarly, the loss on the next day (June 5) was 0.07 in. (the third day of decline in moisture column B), giving a soil moisture of 1.06 in. at the end of June 5.

A day-to-day analysis of the soil moisture index for all days in the 50-yr. period from January 1918 to December 1967 was made using the method described.

4. WORKDAY MODEL

CONCEPT OF WORKDAYS

The series from the soil moisture index model was combined with the data from the construction projects to produce a series simulating working conditions. Four "work" categories are defined by the engineers of the Missouri State Highway Department, namely: A holiday, Saturday, or Sunday, when no work was to be done (symbolized by 0); a normal workday without any "weather" restrictions (symbolized by 1); a no-work day due in the main to weather/soil moisture conditions (symbolized by 2); and a partial or restricted workday (symbolized by 3). As will be appreciated, the classification of days into 1, 2, and 3 depends on a number of things including the type of work being carried out. Nevertheless, the workday index for the main road construction period of April to November appeared to be reasonably representative of working conditions as they apply to road construction.

To apply these classifications of workdays to the daily climatic record for Jefferson City, a preliminary analysis was made by comparing the daily precipitation and the computed soil moisture index for several hundred days in the 1965–68 period with the actual workday classification for the two road construction jobs in the Jefferson City area. The analysis showed that in most cases it was possible to estimate the workday classification based on a consideration of daily precipitation and the computed soil moisture index. In brief, workdays were defined in terms of the precipitation and soil moisture as follows:

1. If soil moisture was 1.79 or greater, the workday was classified as 2 (no work).
2. If the soil moisture was within the range 1.60 through 1.78, the workday was classified as 3 (partial work), unless the precipitation for the day was greater than twice the maximum soil moisture loss as given in the appropriate column of table 1. In the latter case, it was classified as 2 (no work).
3. If the soil moisture was more than 1.40 and less than 1.60, the day was classified 2 (no work) if the precipitation for the day was greater than twice the maximum soil moisture loss as indicated by the appropriate column of table 1 or 1 (full work) if the day was the third (or more) daily decline in the soil moisture index. If *neither* of these conditions applied, the day was classified 3 (partial work).
4. If the soil moisture index was 1.40 or less, the day was classified as 1 (full work), except if the precipitation was greater than 0.4 times the maximum soil moisture loss for that particular moisture zone, in which case it was classified 3 (partial work).

The procedure is more systematically described in the flow chart presented in figure 1. Using the procedure described in the flow chart, the soil moisture series is translated into a series indicating working conditions. In figure 2, the soil moisture index is plotted with the corresponding working day classifications to give a somewhat more intuitive idea of the conditions defining the transformation.

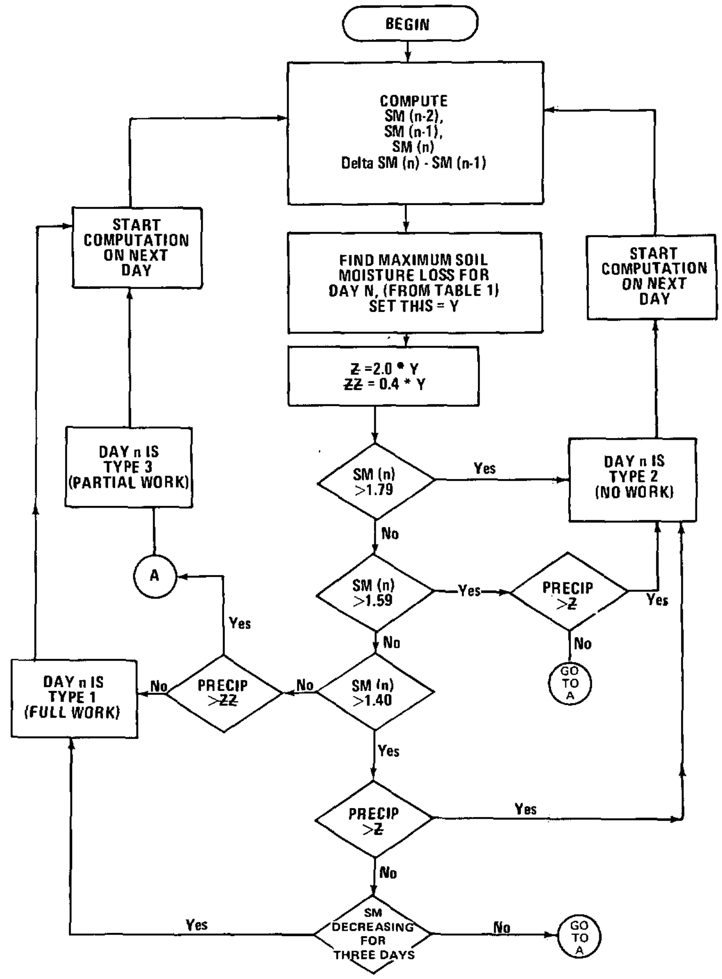

FIGURE 1.—Flow chart for translation of soil moisture index values into work classification values.

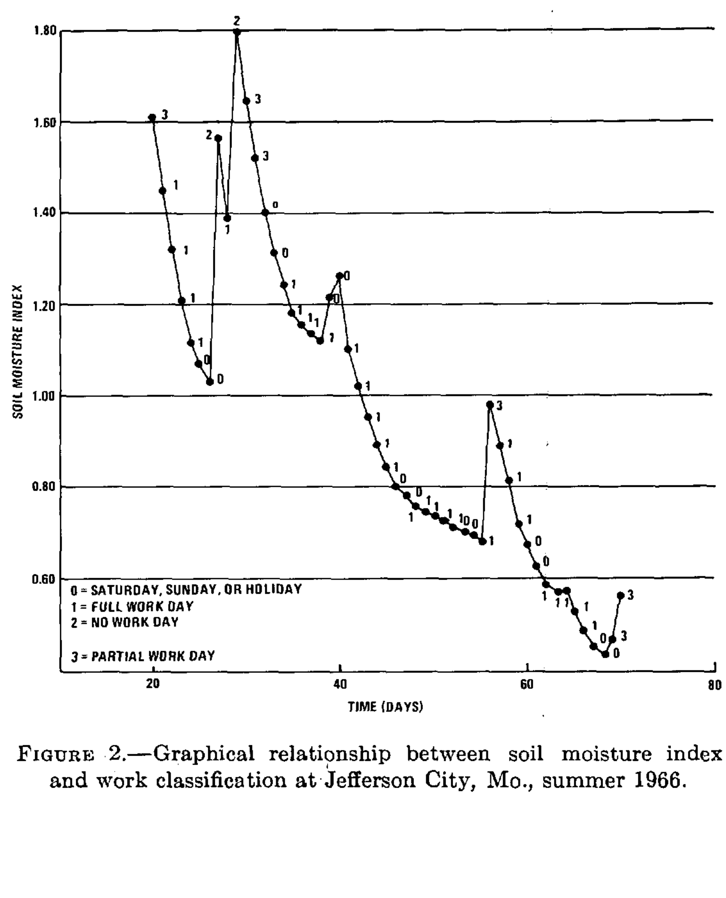

FIGURE 2.—Graphical relationship between soil moisture index and work classification at Jefferson City, Mo., summer 1966.

COMPARISON OF ACTUAL AND PREDICTED WORKDAY CLASSIFICATIONS

The model just described was designed to produce a series of numbers that can be interpreted in terms relevant to the road building industry. To verify or test the capability of the model, actual daily operational records were compared to the output of the model for the period covered by the two sample highway construction projects.

The comparative data were placed in contingency tables for two sample periods, and the χ^2 test was applied. For the sample period of April through October 1966, $\chi^2=61.6$. For the sample period of April through October 1968, $\chi^2=110.1$. At the 0.05 significance level and with four degrees of freedom, the tabular value of χ^2 is 9.5. This led to rejection of the hypothesis that the series of work categories produced by the model differed from those observed. It then seemed reasonable to conclude that the model did produce acceptable workday classification "observations."

MARKOV CHAIN PROBABILITY MODEL

The output of daily values of the work index for a 48-yr period is voluminous in its raw form. Some of the patterns that emerge from this long series of computed values can best be portrayed in terms of monthly or seasonal averages, as presented in the latter sections of this paper. In addition, the information can be used in a summarized form in terms of expressions for initial and transitional probabilities of Markov chains. These estimates are particularly useful in viewing the persistence of sequences of favorable working conditions.

Feyerherm and Bark (1965, 1967) used a first-order Markov chain probability model to study persistence of weather patterns. They defined two classes of days; that is, "wet" or "dry." A day was classified as wet if precipitation on that day exceeded the threshold value. The Feyerherm and Bark method can be applied to the soil moisture/workday model by combining the classifications and defining an "F" day as one which would allow full road construction work (type 1 day), and an "N" day as one which will not allow full work (type 2 or type 3 day). Estimates of the probability of sequences of dry or wet days based on initial and transitional probabilities obtained in this way may be more relevant to road building operations than those obtained from Feyerherm and Bark's model, which is based on precipitation alone.

To establish the suitability of the Markov process as a characterization of working conditions, let $P(R_t, R_{t+1}, R_{t+2}, \ldots, R_{t+n})$ be the probability of a given sequence of wet or dry days—wet and dry days being defined as above—letting t and $n=1, \ldots, 365$. The order of Markov chain used to estimate the probability of such sequences was chosen on the basis of tests defined by Anderson and Goodman (1957) and applied by Feyerherm and Bark (1965). The appropriateness of a first-order Markov process was initially examined by testing the hypothesis $P(R_t \mid R_{t-1})=P(R_t) \cdot P(R_{t-1})$ against the alternative hypothesis $P(R_t \mid R_{t-1}) \neq P(R_t) \cdot P(R_{t-1})$. A 48-yr series of sample observations of R_t, R_{t-1} was obtained from the output of the workday model. These sample data were assembled in a series of 2×2 contingency tables, from which χ^2 statistics were computed. Results of these computations are shown in table 3. The hypothesis $P(R_t \mid R_{t-1}) =P(R_t) \cdot P(R_{t-1})$ was rejected for each of the periods represented in table 3. At the 0.05 level, the sequence of dry or wet days relevant to road building near Jefferson City is therefore characterized by at least a first-order Markov process.

To check the possibility that a second-order Markov process should be employed, we tested a second and related set of hypotheses with the sample. The null hypothesis (indicating a first-order Markov process) is $P(R_t \mid R_{t-1}, R_{t-2})=P(R_t \mid R_{t-1})$. This was compared to the alternative—suggesting a higher order Markov process—$P(R_t \mid R_{t-1}, R_{t-2}) \neq P(R_t \mid R_{t-1})$.

As shown in table 4, computation of 16 sample period χ^2 statistics leads to the acceptance of the null hypothesis in 11 cases and rejection in five cases. As a result of these tests, we concluded that the probability of a sequence of full workdays and not full workdays, expressed in terms relevant to road building work near Jefferson City, Mo., should be estimated from a Markov chain probability model of at least order two. Probability estimates based

TABLE 3.—*χ^2 values from contingency table computations (1918–65)*

Sample period	χ^2
January 10–30	26.2
February 4–24	31.6
March 1–21	45.7
March 26–April 15	77.4
April 20–May 10	47.0
May 15–June 4	53.6
June 9–29	55.7
July 4–24	28.9
July 29–August 18	28.3
August 23–September 12	34.2
September 17–October 7	43.2
October 12–November 1	25.0
November 6–26	23.6

TABLE 4.—*Sample frequency data for computing χ^2 statistics, Jefferson City, Mo., May–November 1918–65*

Month	R_{t-1} Dry	R_{t-1} Wet
April	0.40*	0.42*
May	0.53*	1.28*
June	0.24*	8.17
July	1.17*	7.03
August	0.68*	4.04
September	0.34*	0.08*
October	0.08*	8.93
November	0.28*	6.19

*$P(R_t \mid R_{t-1}, R_{t-2})=P(R_t \mid R_{t-1})$ not rejected

TABLE 5.—*First- and second-order Markov chain probability estimates (based on daily work index computations for Jefferson City, Mo., 1918–66)*

25-day period ending	$P(F)$	$P(F\|F)$	$P(N\|N)$	$P(F\|F,F)$	$P(F\|N,F)$	$P(F\|F,N)$	$P(N\|N,N)$
March 21	0.575	0.795	0.744	0.819	0.459	0.691	0.811
April 15	.538	.884	.771	.809	.219	.863	.769
May 10	.542	.766	.776	.740	.323	.837	.816
June 4	.496	.752	.801	.745	.044	.774	.761
June 29	.546	.800	.781	.815	.213	.739	.778
July 24	.734	.880	.592	.881	.409	.869	.595
August 18	.717	.865	.596	.865	.466	.866	.638
September 12	.738	.897	.613	.923	.458	.738	.647
October 7	.647	.833	.742	.830	.436	.866	.818
November 1	.683	.823	.618	.832	.691	.777	.780
November 26	.734	.857	.599	.849	.411	.913	.606

F is used to denote R_t= full workday at t, and N is used to denote R_t=not full workday. The t subscripts have been dropped for convenience.

TABLE 6.—*Probability that there will be at least n full workdays in a 5-day workweek chosen at random from the 25-day period shown in the first column*

25-day period ending	Number of full workdays[a] in 5				
	5	4	3	2	1
March 21	0.251	0.445	0.586	0.710	0.831
April 15	.334	.479	.615	.734	.838
May 10	.168	.354	.520	.680	.806
June 4	.154	.259	.444	.643	.821
June 29	.236	.379	.533	.684	.833
July 24	.442	.657	.812	.911	.967
August 18	.401	.639	.793	.895	.956
September 12	.521	.691	.805	.890	.958
October 7	.303	.527	.660	.769	.856
November 1	.324	.613	.755	.841	.907
November 26	.385	.626	.799	.909	.965

[a] For example, the probability of having at least 4 full workdays is computed as the summation of the following probabilities: $P(F,F,F,F,F)+P(N,F,F,F,F)+P(F,N,F,F,F)+P(F,F,N,F,F)+P(F,F,F,N,F)+P(F,F,F,F,N)$.

on these two types of Markov processes are shown in table 5.

Given that a day can be either wet or dry, there are 32 different possible sequences for a 5-day workweek. We assumed a second-order Markov process and used the probability values from table 5; the probability that each of the 32 possible sequences would occur was computed. The results were combined and these are presented in table 6. The results conform to the conventional ideas regarding the superiority of July, August, and September as months for road building activity. Such information, in addition to its usefulness for planning in its present form, could be employed as input data for more sophisticated types of management decision models.

FREQUENCY OF FULL AND PARTIAL WORKDAYS AND NO-WORK DAYS

The series of workdays obtained from the computed soil moisture index, described in an earlier section of this paper, is summarized in this section. A monthly summary of the data for the months April through October is shown in table 7.

TABLE 7.—*Frequency of simulated operational data (excluding weekends) for Jefferson City, Mo., April–October 1918–67*

Month	Full workday		No-work day		Partial workday		Total number of days
	Number of days	% of days	Number of days	% of days	Number of days	% of days	
April	553	52	144	13	374	35	1,071
May	587	53	159	14	361	33	1,107
June	601	56	152	14	319	30	1,072
July	800	72	87	8	219	20	1,106
August	775	70	92	8	241	22	1,108
September	720	67	116	11	236	22	1,072
October	748	68	102	9	256	23	1,106

TABLE 8.—*Comparison of the number of full workdays and no-work days at Jefferson City, Mo., April–October 1918–67*

Month	Full workday		No-work day	
	Excluding weekends (%)	Including weekends (%)	Excluding weekends (%)	Including weekends (%)
April	52	51	13	14
May	53	52	14	15
June	56	56	14	14
July	72	72	8	8
August	70	69	8	9
September	67	69	11	10
October	68	68	9	10

The data in table 7 are for all Monday through Friday workweeks in the 50-yr period considered. The seasonal pattern is clear; there is a maximum percentage of full workdays in the period July to October and a minimum percentage in April and May. For example, in April, 52 percent of the days were "full work," compared with 13 percent which were "no work" and 35 percent which were "partial work." These data may be contrasted with those for July where the corresponding percentages are 72, 8, and 20. Further, the combined months of April and May in the 50-yr period 1918–67 had 1,140 full workdays compared with 1,575 such days in July and August.

A similar analysis was made for all of the days in the period including Saturdays and Sundays. The monthly summary including the additional two days is given in table 8. As can be seen, there is little difference between the values which result from the two assumptions regarding possible workweeks.

5. APPLICABILITY TO INDEX OF WORKABILITY

One direct application of the information produced by the simulation model is the calculation of an index of workability.[7] This is essentially an index of whether work can or cannot be done. The actual "workability index" employed in this discussion is calculated by computing the number of work hours and expressing this as a per-

[7] Other applications of the simulation model discussed in this paper are being presented in a companion paper (Maunder et al. 1971).

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TABLE 9.—*Workability index for Jefferson City, Mo., 1918–67*

Month	Highest (year)	Mean (s.d.)[a]	Lowest (year)	Range
April	0.92 (1956) (1959)	0.69 (0.12)	0.38 (1922)	0.54
May	0.94 (1934)	.69 (0.12)	.42 (1935) (1938)	.52
June	1.00 (1936)	.71 (0.15)	.45 (1935)	.55
July	0.97 (1940)	.82 (0.09)	.60 (1961)	.37
August	0.97 (1960)	.80 (0.09)	.61 (1952)	.36
September	0.98 (1939) (1940) (1950)	.79 (0.12)	.48 (1926)	.50
October	0.98 (1964)	.79 (0.11)	.39 (1941)	.59

[a] Standard deviation

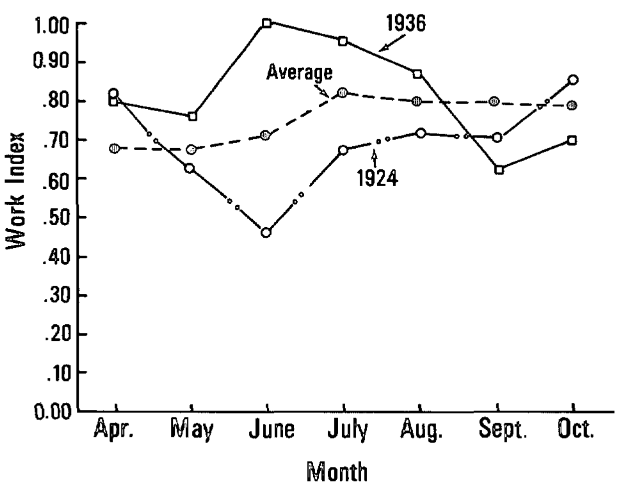

FIGURE 3.—Comparison of work index values for the wet year 1924 and the dry year 1936, April–October.

centage of a total possible number of work hours. For this analysis a full workday is considered to be 8 hr, a no-work day is 0 hr, and a partial workday is 4 hr. These values are arbitrary and could be varied according to circumstances, but they are believed to be a reasonable approximation of what actually occurs.

The workability index was computed on a daily basis—considering all days including Saturdays and Sundays—for Jefferson City from 1918 through 1967. The extremes, means, and standard deviations for the months April through October are given in table 9. These data show that, on the average, 70–80 percent of the total possible time could have been worked, the monthly average in the construction season varying from a low of 69 percent in April and May to a high of 82 percent in July. The highest percentages for the 50-yr periods were in all cases above 90 percent, and in 7 mo they were at least 97 percent. By contrast, in April 1922, the index indicated that only 38 percent of the possible work could have been done.

The actual workability index for two selected years (1936 and 1924) is shown graphically in figure 3, 1936 being a dry year for road construction, and 1924 a wet

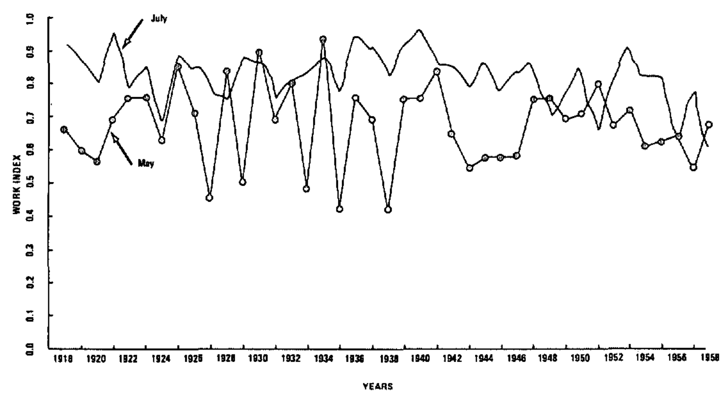

FIGURE 4.—Work index value variation at Jefferson City, Mo., May–July 1918–58, if weekends are included as workdays.

year. Similar graphical analyses were obtained for all years, and a graph showing the variation in the work index in May and July for the 41-yr period 1918–58 is shown in figure 4. Both graphs show the variation in the work that could have been done using all days including weekends, and the difference between a wet May and a dry July is evident in most years.

6. CONCLUSIONS

The simulation model discussed in this paper is based on a comparatively short 4-yr record for two road construction projects, and a comparatively long 48-yr record of daily meteorological observations. Application of the model to generate "experience" over a 48-yr period appears to have been successful, and it is reasonable to claim that it is potentially more useful to managers of road construction projects—at least as far as central Missouri is concerned—than either a short period of operational records or a long period of weather records taken separately.

Potential application of this and similar such simulated series of workdays to economic problems resulting from road construction activities are quite apparent. In particular, with more complete operational data and with further refinements in the model, a long series of simulated workability index values could be used in long-term planning, bidding strategy, and contract negotiations.

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